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THE DEFORMATION AND FAILURE MECHANISMS OF PAPER IN SHORT SPAN COMPRESSION

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We examine the difficulties associated with predicting the compressive strength of fibrous structures by considering the case of a paper sheet. While a single sheet of paper undergoes global buckling when subjected to compressive forces, buckling is not the dominating failure mode in some applications. For example, the ultimate strength of paper boxes is governed primarily by material failure originating at the corners. The micromechanical mechanisms behind the compressive failure on the microscopic level are generally difficult to investigate mainly due to the experimental difficulties. Among them is properly restraining slender test samples in physical experiments, which is required to discriminate between different failure modes during compression test of paper.

While many analytical and numerical frameworks exist for predicting the mechanical response of randomly oriented fibrous networks, their applicability is often limited to certain load cases, such as the uniaxial tensile test. The damage and failure mechanisms under other load conditions, such as compression, shear and bending are in fact quite dissimilar to the ones observed under uniaxial tension. A direct manifestation of such differences is a large discrepancy between tensile and compressive failure stresses and strains of paper.

We show that the network response in compression can be captured using a network of interconnected fibers described with Timoshenko beams and beam-to-beam contacts. Unlike a tensile load, where an increased load leads to straightening and activation of fibers in the network, a compressive load increases the importance of bending deformation. In contrast to ordered composites fibers which can be aligned with the load, the natural curl and random nature of paper means that there is never a significant proportion of fibers oriented parallel to the applied load. Due to the importance of bending, the anisotropic nature of fibers themselves can have a large influence on the network response. Using a three-dimensional volumetric model, we show how the shear stiffness of individual fibers must be adapted to account for the anisotropic material response.

Finally, we use the developed model to investigate the edgewise compressive strength of paper, which is one of the standard properties used for predicting paper box strength. Combining network and single fiber simulations, we show that the edgewise compressive strength of packaging material cannot be governed by fiber level buckling, and nor is it necessarily the result of initially defective regions. Rather, the load-bearing capacity of a sheet decreases with an onset of delamination, ultimately causing softening through increased flexibility. In the physical tests used to characterize edgewise compressive strength, the resulting load asymmetry causes out-of-plane deformations seen in the post-failure response.